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Quantized conductance and electron focusing spectra of GaAs/AlGaAs point contacts fabricated by optical lithography

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Split gate quantum point contacts on a two-dimensional electron gas (2DEG) of GaAs/AlGaAs heterostructures are fabricated using conventional optical lithography. The typical opening of the split gates ranges from 0.25 to 0.5 μm . Applying negative voltages to the gate introduces horn-shaped constrictions. In a double point contact device, the point contact conductances are measured as a function of gate voltage, and transverse electron focusing is studied using one point contact to inject electrons ballistically into the 2DEG and the other to collect the electrons. Clear quantized conductance steps in units of $2e^2/h$ are found at temperatures between 0.1 and 2 K. Also, electron focusing spectra are obtained for various point contact widths and some features are characterized by the geometry of the split gate.

Quantum point contacts (QPCs) in a high mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures show conductance quantization in units of $2e^2/h$ when the contacts are gradually pinched off. Split gates are used to vary the contact width. Quantized conductance is a consequence of the stepwise increase of the number N of occupied one-dimensional (1D) subbands, each of them contributing $2e^2/h$ to the conductance. Since the discovery of quantized conductance,^{1,2} there have been intensive studies on this system both experimentally and theoretically.³ The study of QPCs provides an understanding of 1D ballistic transport of electrons. On the other hand, QPCs can be used to examine phenomena, such as transverse electron focusing,⁴ edge channels in quantum Hall regime,³ and Andreev reflection in superconductor-semiconductor interfaces.⁵⁻⁷ A potential application of QPCs is far-infrared detection in the frequencies above 1 THz.⁸

To observe quantized conductance steps in QPCs, a He temperature mobility of $1 \times 10^6 \text{ cm}^2/\text{V s}$ and split gates with a submicron opening are usually required. Therefore, GaAs/AlGaAs heterostructures are chosen, and electron beam lithography (EBL) is needed to define split gates. Another possible way to fabricate the gates is to use optical lithography (OL). The advantages of OL are that in contrast to EBL it does not introduce radiation damage in the 2DEG. Also for device applications the use of OL is attractive. However, the disadvantage is that the ultimate resolution of conventional OL is about 0.5 μm . For QPCs, the widths can be fortunately reduced by applying negative voltages to the split gate.

The fabrication of QPCs using OL instead of EBL has already been reported.⁹ Although a signature of quantized steps was found, the quality of the steps is worse than that usually observed in EBL defined QPCs. It is thus not clear that QPCs defined by OL can also show well-defined quantized steps.

In this letter, we report measurements of quantized conductance and transverse electron focusing in a double point contact device fabricated by conventional optical lithography. We developed a fabrication process that allows us to realize the split gates with a submicron opening.

Our starting sample is a MBE grown GaAs/AlGaAs heterostructure. The measured sheet electron density and mobility at 1.2 K are $3.4 \times 10^{11} \text{ cm}^{-2}$ and $9.2 \times 10^5 \text{ cm}^2/\text{V s}$, giving an electron mean free path ℓ_e of 9.2 μm .

The QPC fabrication is as follows. On a sample of $6.5 \times 6.5 \text{ mm}^2$, ohmic contacts were first made by allowing NiAuGe. The split gates were then defined using the OL and lift-off technique. In the gate process, a layer of 0.8 μm thick Shipley S1400-25 positive photoresist was coated. Because the resist within a distance of $\sim 0.5 \text{ mm}$ of the sample edge is much thicker than elsewhere, good contact between a mask plate and the resist at the center of the sample cannot be obtained. Consequently, the resolution becomes poor. To solve this, before patterning gates, we first exposed the edge for 60 s and removed the resist in a developer MF312:H₂O=1:1 for 7 s. The mask used has a rectangular pattern covering the middle area of the sample. Then, gate patterns were exposed in the UV300 mode and also high pressure mode. After the sample was soaked in chlorobenzene, the patterns were developed in the same solution. To work with the UV300 mode, we used a quartz mask prepared by EBL. It contains the patterns of a split gate, the opening of the gate being 0.25 μm and each side of the gate being shaped as a wedge of 30°. A layer of Au/Ti is used for the gate. Finally, a Hall bar geometry was patterned by wet etching.

Our devices are schematically illustrated in Fig. 1(a). The separation between two QPCs is 4.4 μm , and the opening of the split gates ranges from 0.25 to 0.5 μm . Figure 1(b) shows a SEM micrograph of a device, of which measurement results will be reported. As one can see, the split gate to define the QPCs has a saddle shape in contrast to the sharp wedgy one defined in the mask.

Our measurements were done either in a ⁴He cryostat or a ³He/⁴He dilution refrigerator, using a standard ac lock-in technique. In the first experiment, we measured the resistance of a QPC as a function of gate voltage with a constant current of 2 nA and at 0.1 K. As expected for good QPCs, plateaus are observed in the resistance in the gate voltage V_G

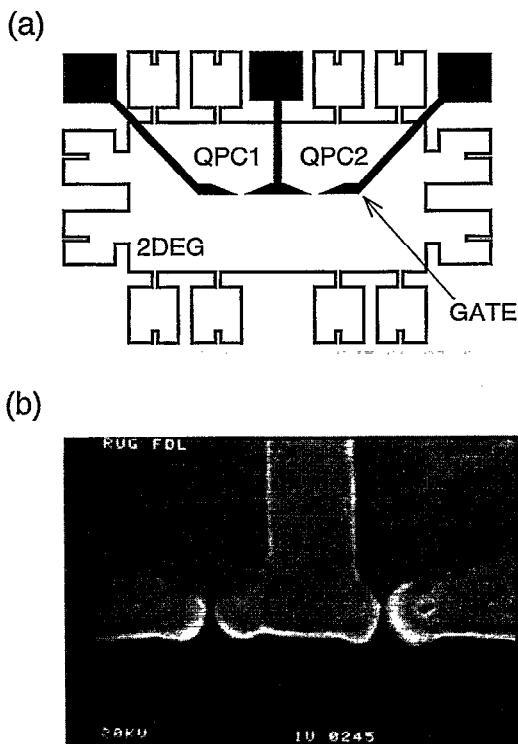


FIG. 1. (a) Schematic layout of the devices. The split gate defines double point contacts, QPC1 and QPC2, with a separation of $4.4 \mu\text{m}$; (b) SEM micrograph of a split gate defined by optical lithography for a device, of which the results are obtained and discussed. The bar in the micrograph is $1 \mu\text{m}$.

between -2.3 and -1.5 V. The conductance vs V_G for the two QPCs in the device is plotted in Fig. 2. In total, nine steps approximately at multiples of $2e^2/h$ were found. Structure in the conductance for higher index steps is partially due to noise. In the calculation of the conductance, a resistance of 200Ω was subtracted and is assumed to be the series resistance of the wide 2DEG leads. Near the pinch-off voltages, steps are more pronounced and show comparable quality as

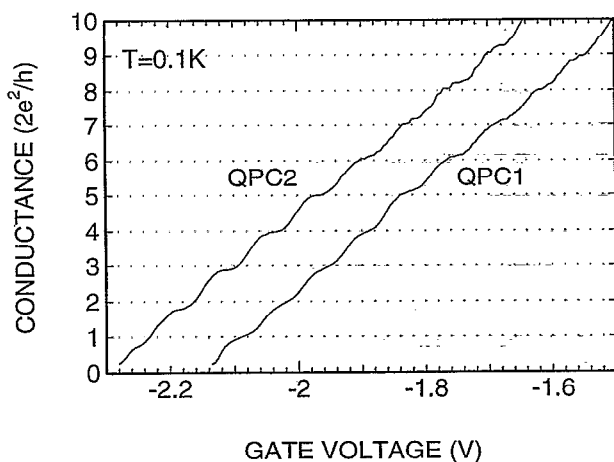


FIG. 2. Conductance in units of $2e^2/h$ as a function of gate voltage at 0.1 K for the two quantum point contacts in the device.

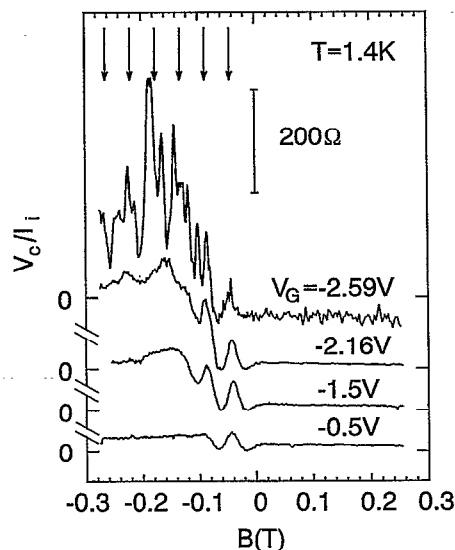


FIG. 3. The four terminal longitudinal resistance V_c/I_i of the double point contact device as a function of perpendicular magnetic field for four gate voltages at 1.4 K , where V_c is the collector voltage and I_i the injector current. The point contact widths decrease roughly from 250 nm for $V_G = -0.5 \text{ V}$ to 20 nm for $V_G = -2.59 \text{ V}$. The theoretical peak positions for classical focusing effect are indicated by arrows.

reported for QPCs fabricated using EBL. Furthermore, measurements of the conductance at temperatures between 0.1 and 4.2 K show that the quantized steps can only be resolved below 2 K , in contrast to results in QPCs using EBL, in which they can be observed at 4.2 K .

The quantized conductance steps are expected in QPCs if the channel lengths are shorter than the mean free path. However, experiments^{10,11} in EBL point contacts with channel lengths $\geq 0.6 \mu\text{m}$, show no conductance steps. One of the arguments for the absence of the steps is boundary scattering due to the irregularities of the channel wall. In our devices, as shown in Fig. 1(b), the shape of the split gate is not well defined if one compares it with that of EBL QPCs. The channel length is about $1 \mu\text{m}$ and seems to be quite long. Our clear observation of the steps is thus remarkable. We interpret our results as due to a shorter effective channel near the pinch off resulting from a horn-shaped constriction [see Fig. 1(b)]. Using the classical resistance expression for point contacts¹ ($R = 450 \Omega$ before the subtraction of the series resistance), we found the point contact widths of $0.65 \mu\text{m}$ around $V_G = -0.6 \text{ V}$. Surprisingly, they are considerably wider than the opening of the split gate. The reason for this is not clear.

In the second experiment, we measured transverse electron focusing in the same device by varying the magnetic field. The QPC2 is used as an injector to inject a divergent beam of electrons ballistically into the 2DEG, and the QPC1 is applied as a collector to detect the electrons after one or more specular reflections at the boundary between two QPCs. Classical electron focusing has also been studied in GaAs/AlGaAs 2DEGs using narrow wires as injectors and collectors.¹²⁻¹⁵ Figure 3 shows the longitudinal resistance, the ratio of the collector voltage (V_c) to the injector current

(I_i), as a function of magnetic field for four gate voltages. The gate voltages are simultaneously applied to both QPCs. An additional small voltage is added to QPC2 because of its more negative pinch-off voltage. Consequently, the width for both QPCs can be changed almost equally. In one of the applied field directions, peaks are found in the resistance V_c/I_i . The observed features can be summarized as follows. (a) At $V_G = -0.5$ V, which is near the channel depletion threshold, the contact widths are relatively wide; the point contacts are in the classical regime. Only the first peak can be observed. By decreasing V_G to -2.16 V, subsequent peaks also occur. However, the amplitude of the peaks with higher index is reduced. This result is different from that found in EBL defined QPC,⁴ where it increases slightly. (b) At $V_G = -2.59$ V, for which both contacts have a resistance of ~ 20 k Ω (quantum regime),¹⁶ focusing peaks can be obtained, but they behave differently and a fine structure is superimposed. (c) In addition to the peaks, a resistance background is found, that increases with reducing V_G . It is characterized by a maximum around -0.16 T, corresponding to a cyclotron diameter of ~ 1 μm .

Theoretically, classical focusing peaks arise each time the magnetic field B is at multiples of $2\hbar k_F/eL$, where k_F is the Fermi wave vector, and L the separation between two QPCs. For our device, $2\hbar k_F/eL$ is 44 mT for the experimental values $L = 4.4$ μm and $k_F = 1.5 \times 10^8$ m^{-1} . For a comparison, the theoretical peak positions are indicated by arrows in Fig. 3. The positions of the observed peaks are consistent with them. The observation of the higher index focusing peaks requires high specular reflection at the boundary defined by the gate. The feature in (a) suggests an increase of the specularity if V_G is reduced.^{13,14} The reduced amplitude for the higher index peaks and the dependence of the background on the field may be related to the fact that, when the field exceeds -0.16 T, the cyclotron radius becomes comparable with the curvature of the horn-shaped boundary. Consequently, trajectories of electrons from the injector are affected. However, a detailed explanation is still not known. For the fine structure in (b), similar results are reported and interpreted as a manifestation of quantum coherent electron focusing, or quantum interference of electrons in magnetic edge states in the 2DEG.⁴ To observe this effect, it is required that the correlation energy $\hbar v_F/L$, the energy needed to randomize a given phase for the electrons traveling over the distance between two QPCs, should be larger than $k_B T$, where v_F is the Fermi velocity. In our case, because of the larger L and the relatively higher temperature ($T = 1.4$ K), this condition is however not satisfied and therefore the fine structure cannot be attributed to this effect. We speculate that our result is due to quantum interference taking place in the horn-shaped opening region of the injector that induces fluc-

tuations in the distribution of electrons in the edge states. The interference should also occur for the collector.

In conclusion, we successfully fabricated double quantum point contacts using optical lithography. Clear quantized conductance steps in units of $2e^2/h$ are obtained in the QPCs. Additionally, the dependence of transverse electron focusing on the point contact width is observed. The results demonstrate that the performance of the devices is comparable to that of quantum point contacts defined by electron beam lithography.

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